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Agricultural Memorandum No 908

Weather and Spray Drift Part II: Some quantifications

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SUMMARY

The influence of meteorological factors on the drift of spray drops produced by a conventional hydraulic sprayer operated at 250kPa pressure is discussed, and simple quantitative treatments are provided, to estimate numbers of drops likely to become airborne initially, and to calculate the consequent pattern of deposit densities downwind of the sprayed area. An attempt is also made to quantify the hazard to sensitive crops from toxic vapour volatolized from nearby sprayed fields which is drifting downwind. Some important aspects of crop spraying for which our present understanding appears to be inadequate are identified and suggestions for further experimental and theoretical work are outlined.

1. Introduction

Part I (Agricultural Memorandum No. 907) has discussed a number of widely - held misconceptions of the ways in which weather influences spray drift, and has indicated in general terms the true role of weather in the various cases considered. The present concern and controversy over spray drift reflects not only misconceptions but also our ignorance of several of the processes involved. However there is a considerable amount of information in meteorological and other literature which, when assembled, allows useful descriptions to be given of many of the effects of weather on crop-spraying. Some data of critical importance in the quantitative estimation of spray drift are lacking. In spite of this it is hoped that the present write-up will provide useful general guidance on the interrelations between drift and weather, and may also serve to stimulate experimental work on important processes not yet fully understood.

A brief reference at this point to the layout of the report may be helpful to the reader. Section 2 defines the spraying system and introduces the main meteorological variables to be considered. Section 3 discusses in qualitative terms these variables in the context of drift. Section 4 develops the quantitative aspects of weather and drift: those not interested in the mathematical detail will prefer to pass quickly over parts of this but it is recommended that the section is not ignored completely because it discusses many of the difficulties of the drift problem qualitatively as well as quantitatively, and underlines the major assumptions which have had to be made to progress towards quantitative results. Section 5 highlights the major points in the previous sections.

2. General influences of weather on spraying

Much of the concern over spray drift is connected with herbicides, and it is convenient therefore to consider in this paper chiefly a conventional hydraulic, boom-mounted spraying system operated about 0.5 m above the crop. Nothing will be

said about controlled-droplet systems producing a narrow size-spectrum of drops: drift from these is probably easier to quantify, so any descriptions of spray drift which is adequate for hydraulic systems will be easily adaptable to CDA systems.

The main components of weather which influence drift are wind (speed and direction), atmospheric stability and temperature and humidity. The broad effects of these quantities may be described conveniently by considering the fate of drops from the instant of production, immediately after emerging from the spray nozzle. A wide range of sizes is produced (see for example Table 1 which shows unpublished NIAE data for drops from two hydraulic fan jets (normal and fine) operated at 250 kPa to spray respectively 200 l/ha and 50 l/ha when conventionally mounted). Wind speed will

Table 1 Drop size spectra from normal and fine 80° fan jets

Diameter range (μm)	% of total volume		Diameter range (μm)	% of total volume	
	normal	fine		normal	fine
0-20	0.1	0.1	200-220	3.2	10.0
20-40	0.1	0.4	220-240	3.7	8.2
40-60	0.2	0.9	240-260	4.1	6.0
60-80	0.3	1.8	260-280	4.5	4.2
80-100	0.5	3.5	280-300	5.0	3.1
100-120	0.8	7.1	300-350	11.9	4.5
120-140	1.1	10.8	350-400	12.6	0
140-160	1.6	13.3	400-500	31	0
160-180	2.2	14.0	>500	14	0
180-200	2.8	12.3	Mass median diameter	380	180

control the number and size spectrum of drops which become "airborne" (to form drift), in contrast to the mainly larger drops which go directly into the crop. The average wind direction and fluctuations from average, determine the places at risk from drift, and the uniformity of deposit over the sprayed area. Atmospheric stability affects the gustiness of the wind and the amount of turbulent mixing occurring in the surface layer of the atmosphere, and has a considerable influence on the time the smaller drops remain airborne. Temperature and humidity will influence the rate at which the drops evaporate, and hence to some extent the time they remain airborne.

3. Qualitative effects of the individual weather elements on sprays

(a) Atmospheric stability

The atmospheric surface layer is usually turbulent, but the amount of turbulence may vary considerably with time. The simplest case is so-called neutral atmospheric stability which occurs usually when the weather is cloudy and windy. Here the turbulence is created entirely by the wind shear (rate of increase of wind speed with height) which results from friction at the surface. The turbulent fluctuations of wind velocity are then directly proportional to wind speed. For example the typical vertical up - and down-drafts in neutral conditions are about one tenth of the mean horizontal wind speed measured at a height of a few metres, and the across-wind and alongwind fluctuations are about twice as large. Thus in winds of 10ms^{-1} (19 knots) a substantial number of the up-drafts will exceed 1ms^{-1}, the fall-speed

of 250 μm drops: it is easy to understand therefore why the drift hazard is serious at such windspeeds.

Turbulence may also be created or destroyed by buoyancy forces resulting from variations of air density with height, which therefore enhance or suppress the turbulence produced by wind shear. An explanation of the effects of buoyancy may be provided simply from consideration of a typical daytime case in summer. Here solar radiation warms the ground which in turn warms the air in contact with it. This air will then be lighter than that in the overlaying layer, and will rise as discrete "bubbles", entraining heavier air, creating additional turbulence and finally coming to an equilibrium height when the buoyancy is exhausted. Similarly cold air overlying the warm layer will tend to sink towards the surface. These conditions are described as unstable or lapse. The degree of instability may be quantified (as a ratio of the turbulence produced by buoyancy to turbulence produced by wind shear), but a simple practical scheme described shortly provides a much more convenient method of assessing atmospheric stability.

In the converse case of stable or inversion conditions the surface is cooler than the overlying air, and the air density decreases significantly with increasing height. In these circumstances a small volume of air when displaced upwards or downwards will become respectively denser or less dense than its surroundings, and after the displacement will tend to return to its original height. In this case the buoyancy forces work to suppress the turbulence created by wind shear, and in conditions of high stability will totally damp out turbulence, with the lower atmosphere then in a state of laminar flow.

The mathematical representation of stability includes the inverse square of the wind speed, demonstrating that windy days or nights will be close to neutral stability. A more convenient working scheme for classifying atmospheric stability has been provided by Pasquill (1961). He introduced 6 stability categories, ranging from A (very unstable) through D (neutral) to F (very stable), and gave a simple method for determining these (Table 2). The value of

Table 2 Pasquill's stability categories

10 m wind (m/s)	Insolation			Night time	
	Strong	Moderate	Slight	4/8 low cloud	4/8 cloud
<2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Strong insolation ≡ sunny midday in summer
Slight insolation ≡ sunny midday in winter
Night = 1 hour before sunset to 1 hour after dawn

Use category D in overcast conditions, and for the hour preceding or following night as defined above.

(In daytime conditions the wind at 1m is about 70% of that at 10m) As a rough guide, 2-3 ms^{-1} at 10m is about Beaufort force 2 ("wind felt on face, leaves rustle"): 3-5ms^{-1} is about force 3 ("leaves and small twigs in constant motion"): 5-8ms^{-1} is about force 4 ("raises dust and loose paper; small branches are moved"): Force 5 is about 8-11ms^{-1} ("small trees in leaf begin to sway").

this scheme is seen by considering the influence of turbulence on the upward diffusion of very small particles: this is a point of some importance in the significance of spray drift and will be considered in detail later in this note. Turbulent diffusion is also one of the factors in the determination of the likely damage to sensitive crops resulting from vapour coming off adjacent areas which have been sprayed by volatile compounds: this hazard will also be discussed in more detail later. For the moment, and for the purpose of illustration, the small particles are assumed to be released from a point near the surface and to diffuse downwind without significant deposition on the surface (this last assumption will not apply to spray drops). Pasquill showed that at a given distance downwind from the source the height to which the cloud of particles had diffused (usually represented by the height at which the particle concentration was 1/10 of the surface concentration)

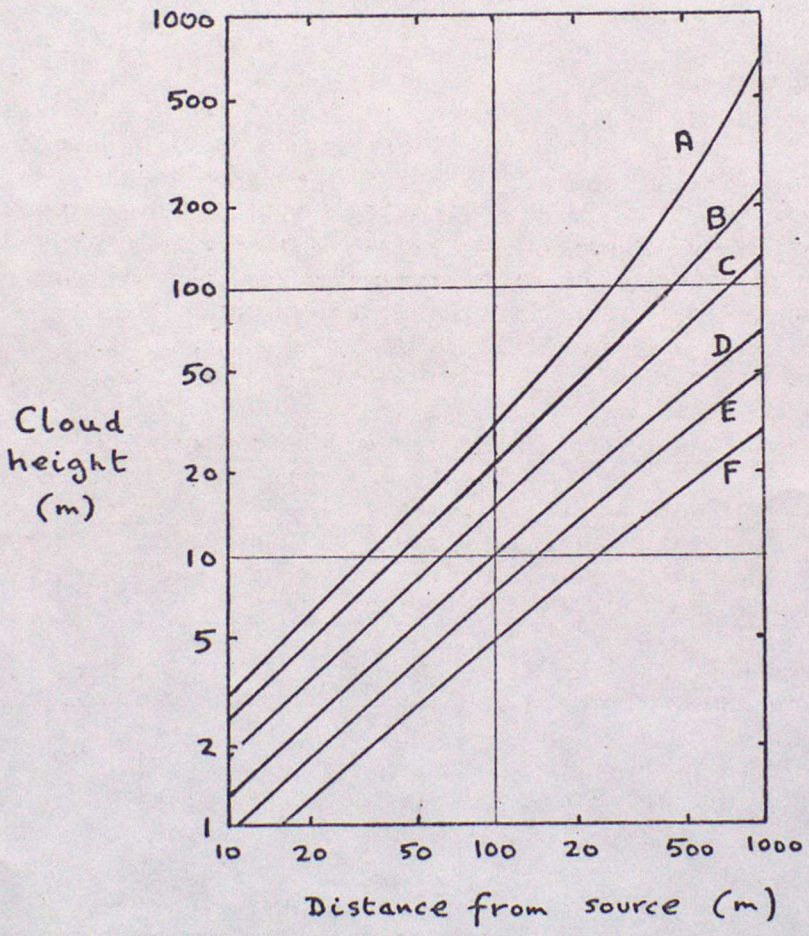

Figure 1. Height of a cloud of small particles at different distances downwind from a source near the surface

was determined almost solely by the stability category. Figure 1 (page 4) shows how this height varies with distance of travel and stability. It is seen that the vertical diffusion is much larger in very unstable than in very stable conditions, and one might expect therefore the former conditions to be much the worst for drift. However the very unstable cases occur only with light winds (Table 2), and in fact proper account of the effects of stability on drift can only be taken in more formal treatments such as outlined later which include separately the influence of stability and wind (the effects of stability on horizontal wind speed and direction are described in the next section).

(b) Wind

The characteristics of the wind are determined by the large-scale horizontal pressure gradients in the lower atmosphere (measured over distances of tens of kilometres), the roughness of the underlying surface, and the atmospheric stability in the lowest few hundred metres. Stronger winds are associated with larger pressure gradients and smoother surfaces. The lightest winds occur with weak pressure gradients. The decrease of wind usually observed at night is a consequence of the increased stability of the atmosphere which reduces the vertical transfer of momentum from the free atmosphere to the surface. The second characteristic of the wind is its gustiness. In the context of crop spraying, which usually takes place over relatively uniform surfaces of only moderate roughness, the major determinants of gustiness are (i) mean wind speed, (ii) atmospheric stability, and (iii) (close to the sprayer only) vortex shedding from the sprayer system and its tractor. It is convenient to quantify gustiness by the intensity of turbulence (root-mean-square fluctuations of wind speed/mean wind speed). The largest values of intensity are associated usually with the most unstable conditions, when in a relative sense the wind is least steady. The intensity is least in near-neutral or slightly stable conditions, but with extreme stability the flow is largely laminer and is then often determined by topography (gravity or "Katabatic" flow) rather than by the large scale pressure field: in these conditions the flow may show large slow changes of direction but these would probably be of little consequence in crop spraying (if this was taking place in these nocturnal conditions) because of the negligable risk of drift (even the smallest drops would settle out fairly close to the sprayer. Relatively large absolute values of turbulence, similar to those with extreme instability, are associated with higher wind speeds, but the implications of the (high) wind speeds on droplet emission process are then extremely important, and to consider drift in terms only of turbulent fluctuations of speed would be misleading in these circumstances.

In very unstable conditions (bright summer days with wind speed less than $3ms^{-1}$) the wind direction sampled over a period of a few minutes shows root-mean-square fluctuations of about 25 degrees, with occasional shorter-term departures of at least 45 degrees. There may also be organised air currents extending down to the surface, associated with convection cloud (cumulus) which often forms on these days, and these can often lead to very large fluctuations of wind direction, and even flow reversal, when the wind speeds are less than about $2ms^{-1}$. The amount of spray which is likely to become drift at these low wind speeds is small but may still present a significant hazard to a sensitive crop which at first sight might not be considered at risk because of its location well off the line of the mean wind direction (or even upwind of the intended spray area).

(c) Temperature and humidity

Temperature is an important variable in assessing the suitability of conditions for spraying, but in most cases will not be a limiting factor. Exceptions include freezing conditions in which some plants may become intolerant of certain chemicals, low temperatures in general which reduce the efficacy of chemical action (e.g. for herbicides), and high temperatures which increase the rate of vapourisation of

chemicals already on plants. These specialised reactions will not be discussed further in this note, although the fate, rather than the production, of vapourised chemicals is considered later.

Humidity may be an important factor in drift. Conventional sprays use an active ingredient diluted by much larger quantities of water. The smaller drops from the mixture evaporate rapidly unless a thin surface film is formed on the drop from components of the active ingredient. If no surface film forms the drops will evaporate until either all the water has disappeared or else a saturated solution of the chemicals in water is attained: over much of the evaporation the rate of loss of water will probably be similar to a pure water drop of the same size. The final size (d) of any drop that remains airborne is given approximately by the expression

$$d = d_o (c(1+p))^{1/3} \qquad (1)$$

where c is the fractional volume of chemical in the original drop of size d_o and p is the volume ratio of water to chemical for a saturated solution. c has a typical value around 0.01, and if p is small the final drop diameter will be 20 - 25% of the original size. Thus if the drops evaporate very quickly after spraying their chance of remaining airborne for a significant time is much improved because their fall speed is rapidly reduced.

4. Some quantitative effects of meteorological conditions on drift

(a) Relationships between wind speed and the proportion of drops which become airborne

Drops ejected from a spray jet have an initial velocity V_o of $\sqrt{2\nu P/\rho}$ where P is the pressure, ρ the drop density and ν the efficiency of the atomisation process (~ 0.8, Goering et. al. 1972). The velocity for drops composed mainly of water is $20 ms^{-1}$ for a pressure of 250kPa. According to Courshee and Ireson (1961) the "stopping distance" S i.e. the distance a drop travels in turbulent air before decelerating to its terminal velocity, after ejection downwards at velocity V_o, is given roughly by

$$S = \left(\frac{d_o \sqrt{V_o}}{1080}\right)^{3/2} \quad \text{(metres)} \qquad (2)$$

where d_o is in μm. Values of S for typical drop user are given in Table 3. Data presented by Goering et. al.

Table 3 Stopping distances for water drops ejected at $20 ms^{-1}$

Drop diameter, d_o (μm)	"Stopping distance", S(m)
25	.03
50	.09
75	.17
100	.27
125	.37
150	.49
175	.62
200	.75
250	1.05

showed that the speed of 100 μm drops decreased to the largest expected turbulent vertical velocities (1 - 2 ms^{-1}) after travelling about 70% of their stopping distance. The results of Table 3 may be used with this percentage to identify the largest size of drop that is likely to become drift when the spray height is 0.5m. Thus one has to determine the drop size for which 0.7S is about 0.5m, on the assumption that all larger drops will enter the crop because their downward velocity is always greater than the maximum likely upward turbulent velocity.

The arguments up to this point have been based on the idea that the drops do not evaporate significantly while decelerating, and that they may be treated independantly of one another even though they are ejected as a spray which induces significant air velocities in the direction of projection of the drop. Goering et. al. were able to use some measurements made by Roth and Porterfield (1965) to provide an indication of the importance of induced air velocity. The measurements were made with a 65 degree fan jet operated at 280kPa and so the results are relevant to the present assumed field spraying case. The expression which was derived for the induced air current V_i at a distance z from the nozzle for droplets of diameter d_o was

$$\frac{V_i}{V_o} = \left(\frac{12}{d_o}\right)^{0.2} \exp\left(-(20z)^{0.67}\right) \qquad (3)$$

Table 4 shows value of V_i calculated from Eq(3).

Table 4 Air velocities (V_i) induced by a 65 degree fan jet with ejection speed, V_o, of 20ms^{-1}

Drop diameter (μm)	V_i (ms^{-1}) after a distance z (m)						
	z=0.1	0.2	0.3	0.4	0.5	0.75	1.0
25	3.51	1.37	0.62	0.31	0.16	0.04	0.01
50	3.01	1.20	0.54	0.27	0.14	0.03	0.01
100	2.67	1.04	0.47	0.23	0.12	0.03	0.01
200	2.32	0.91	0.41	0.20	0.11	0.02	0.01

These induced air velocities result in effective stopping distances larger than those given by Eq(2). The Table indicates that the induced velocities become insignificant for z greater than about 0.5: the choice of a typical height for spraying not usually much greater than 0.5m appears to have some experimental justification therefore.

Comparing Tables 3 and 4 and using some experimental data from Goering et al showing drop speed versus distance suggests that drops have to be significantly less than 150 μm if they are to form drift following ejection downwards from a height of 0.5m. However this conclusion ignores several complicating factors. First the drops from the edge of the spray fan produced by an 80 degree jet have to travel further to reach the crop surface than those in the centre of the fan: on this basis 150 μm drops might become drift in the sense of decelerating to close to their settling velocity while still some distance above the surface. Second, and more important, the results which have been described were obtained with the fan jet operated in still air. An airflow component perpendicular to the spray fan would winnow the smaller droplets out of the airstream induced by the fan, and decrease the distance over which significant induced airflow persists, and affects, the larger drops.

Thus the conclusions from the detailed results of Table 3 and 4 should be applied only when the wind is very light. In very strong winds the induced airflow in the spray fan can probably be ignored after the drops have travelled 0.1m or so, and the stopping distance in Table 3 used as a guide to drift. With these considerations all drops up to 150 μm would be assumed to drift initially, and some of the drops as large as 200 μm projected obliquely from the jet would also contribute to the drift.

A third factor which will upset these deductions is boom bounce. This might move jets near the ends of the boom up and down by say ± 0.3m, alternately increasing and decreasing the initial drift from these nozzles. In particular this will allow significant numbers of drops as large as 200 μm to become effectively drift drops at heights above the crop as high as 0.5 m in windy condtions if they are ejected near the edges of the spray fan, and this gives these crops a much better chance of being carried away in these turbulent conditions, in spite of their settling speed of 0.7 ms^{-1}. The use of stabilised booms provides an advantage additional to the one of securing a more even spray deposit therefore.

The fourth complicating factor is evaporation. Goering et al calculated that the effect of evaporation on water drop diameter was very small during the period of rapid deceleration for drops larger than 100 μ. Smaller drops will evaporate quickly but these are likely to become initial drift in any case, so the influence of evaporation may be ignored at this stage.

On the basis of these considerations a working hypothesis is that in light winds particles larger than 100 μm ejected downwards from a height of 0.5 m at 250kPa will not become drift, but that particles up to 200 μm should be considered in strong winds. Interestingly, these estimates which, while rough, are based on theoretical considerations, agree moderately well with wind tunnel data obtained by Courshee (1959). He measured the size of drops which had a 50% chance of becoming drift at various wind speeds (Table 5). Most drops below this size will form drift, and most above it will settle out at, or very close to, the source.

Table 5 Sizes of drops having a 50% chance of becoming drift ($V_o \simeq 20 ms^{-1}$)

Laboratory wind speed (ms^{-1})	Equivalent field wind speed at 10m* (ms^{-1})	50% drop size (μm)
2.2	4.2	80
3.4	6.6	100
4.0	7.7	160
4.9	9.5	180
6.5	12.5	210

* The laboratory wind was created by a large fan about 2 m upwind from the sprayer and was measured at a height of 0.2 m (the fan height was not given in Courshee's paper but was probably around 0.5 m): in calculating the 10 m wind it has been assumed that the measured wind approximated that at 0.5 m.

Calculations of drift deposits downwind from the source on the assumption of a known initial source strength (Thompson 1979) showed the importance of the effective height of release ** of the drifting drops. On the basis of the previous comments a rough working rule will be that drops up to about 100 μm should be considered in light winds, ($\lesssim 2 ms^{-1}$) and up to 200 μm in strong winds ($\sim 10 ms^{-1}$): tentative estimates of the effective heights of release of these drops given in Table 6 are also based on the earlier discussions. It is stressed that these values are only orders of magnitude

Table 6 Rough estimates of effective release height of the drift component of sprays in light and strong winds (boom height 0.5m, spray pressure 250kPa)

Drop size (μm)	Effective release height (m)		% of spray volume in size range using standard nozzle
	Light winds	Strong winds	
0-50	0.25	0.35	0.3
50-75	0.20	0.30	0.3
75-100	0.10	0.25	0.6
100-125	-	0.20	1.0
125-150	-	0.15	1.5
150-175	-	0.10	2.5
175-200	-	0.10	3.5

estimates, and that fairly extensive field trials, measuring the drift component of sprays over a wide range of wind speeds are required to provide more satisfactory data for future calculations.

(b) The estimation of drift deposit densities downwind of spray area

An approximate method of calculating spray drop deposits at different distances downwind from a source of known strength, based on that given by Bache and Sayer (1975), has been described by Thompson (1979). The treatment assumes that the drops diffuse in the atmosphere in a similar fashion to that described in § 3(a) as they move downwind, except that (i) all drops reaching the surface are assumed to be absorbed rather than reflected and (ii) there is a general settling of the plume at the settling velocity of the drops. Bache and Sayer showed for a monodisperse source of airborne drops sprayed on a line acrosswind at a rate of Q drops per metre length of line the deposit $n(x)$ per square metre at a distance x downwind from the same line is

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** This height is roughly that at which the drops' further motion is determined solely by wind speed and atmospheric turbulence, where motion associated with their original ejection at $20 ms^{-1}$ is insignificant by comparison

$$n(x) = \sqrt{\frac{2}{\pi}} \frac{QAz}{a x^2} \exp\left(-\frac{(z-fx)^2}{2a^2x^2}\right) \qquad (4)$$

where

$f = v_s / \bar{U}$

v_s = settling speed of drops (Table 7)

$\bar{U}$ = mean speed of downwind travel of drops

z = effective height of release of drops

A = function of f and atmospheric stability, increasing from 0.5 for large drops and high stability to 1.0 for very small drops

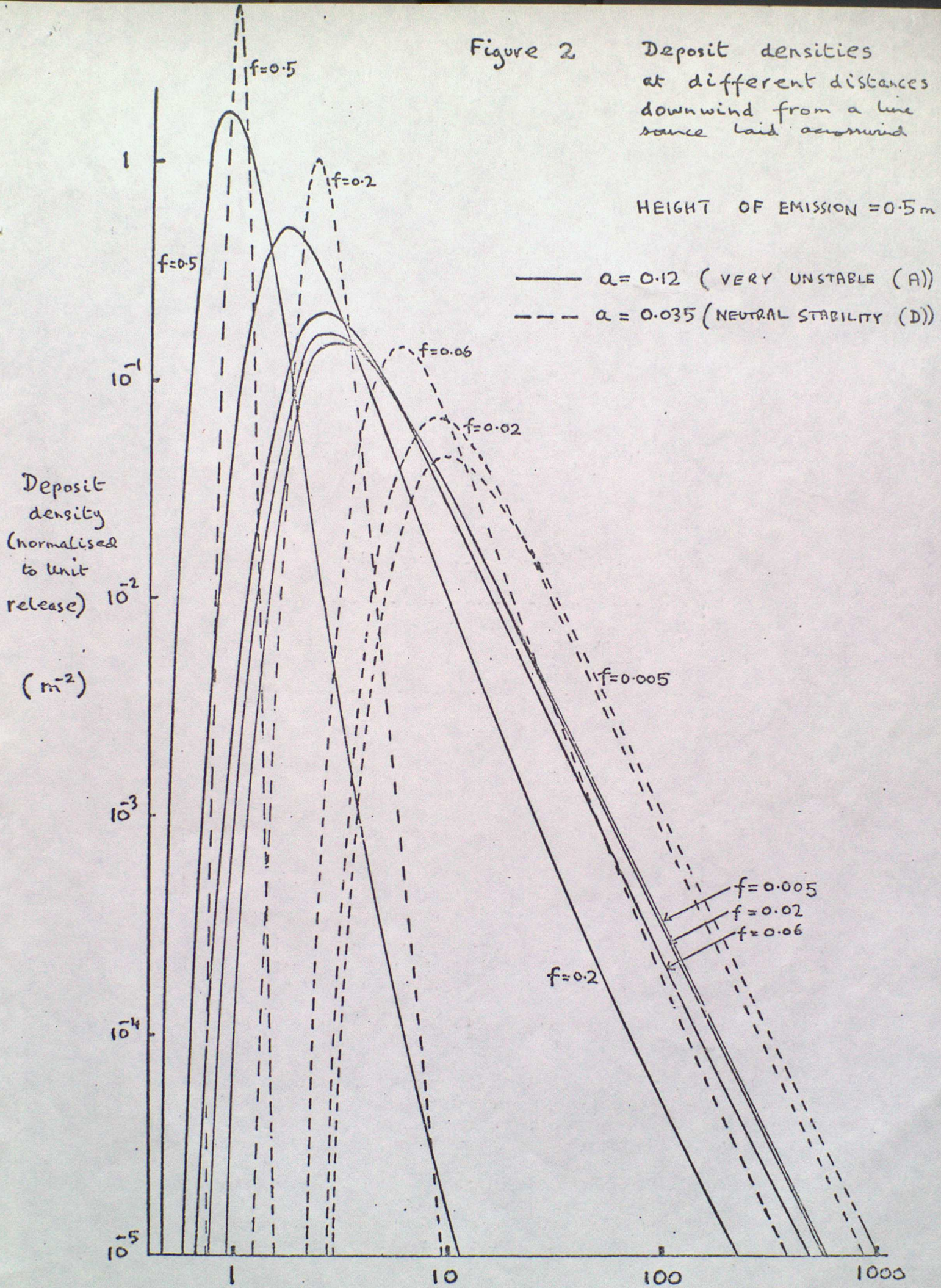
a = 0.12 (Pasquill stability class A)
= 0.067 (Class B)
= 0.035 (Class D)
= 0.013 (Class F)

Table 7 Settling speeds of water drops (Mason 1956)

Drop diameter (μm)	Settling speed (ms^{-1})
20	.01
30	.03
50	.07
100	.25
150	.48
200	.71
250	.93
300	1.15
400	1.60

A feature of Eq(4) is that wind speed appears only implicitly, through source strength, atmospheric stability and the ratio f. An example of the calculated deposit densities downwind from a crosswind line release of 1 "unit" per metre is given in Figure 2 (p 11), for stabilities A and D. It is seen that in very unstable conditions drops for which $f \lesssim 0.1$, released at a height of 0.5m, behave as if "light" (i.e. as if their settling speeds are negligible). These highly unstable conditions will only occur in bright sunshine with winds less than $2ms^{-1}$, for which drops up to about 75μm may be considered "light". The corresponding f-value for 100μm drops would be around 0.2. The influence of atmospheric stability is demonstrated clearly by the diagram. At a given distance from the source the height to which the drops are diffused by atmospheric turbulence (Figure 1) is less in neutral than unstable conditions, and for the light drops this is reflected by higher surface concentrations and hence larger deposit densities well downwind of the source. However, for large f-values the neutral deposit densities are generally less than those in unstable conditions because of larger number falling out near the source in conditions of lower turbulence.

Figure 2 Deposit densities at different distances downwind from a line source laid across wind



The tentative nature of the estimates of source strength of the drift drops given in Table 6 does not justify large numbers of calculations of drift deposit on areas downwind of the sprayed area in many different weather conditions. The result of the application of Equation (4) will be presented for only two cases therefore:

(i) Light winds - very unstable (class A)
- moderately unstable (class B)
- neutral (class D)
- fairly stable (class F)

(ii) Strong winds - here the atmosphere is always close to neutral stability

Light winds are here interpreted as around $2ms^{-1}$ at a height of a few metres, and strong winds as about $10ms^{-1}$. The drift deposit density depends on the alongwind length of the area sprayed, and the distance downwind from this area. The sprayed area is assumed to be very wide (acrosswind) so the effects of lateral diffusion can be ignored. Results are presented in Table 8 for field lengths of 100, 200 and 500m, and for downwind distance between 5 and 1000m. The main features of

Table 8 Estimated drift deposit densities (gm^{-2}) at different distances downwind from fields sprayed at 200l/ha

Wind speed (m/s)	Stability category	Alongwind length of field (m)	Deposit densities (gm^{-2}) at different distances downwind from field edge							
			5m	10m	20m	50m	100m	200m	500m	1000m
2	A	100	.037	.018	.0080	.0025	.0009	.0003	.00006	.00002
		200	.038	.018	.0087	.0030	.0013	.0005	.00011	.00003
		500	.038	.019	.0092	.0034	.0016	.0007	.00019	.00005
	B	100	.052	.025	.011	.0035	.0013	.0004	.00009	.00002
		200	.054	.026	.012	.0041	.0017	.0005	.00015	.00004
		500	.054	.027	.013	.0047	.0021	.0009	.00026	.00009
	D	100	.068	.033	.014	.0043	.0016	.0005	.00010	.00003
		200	.070	.034	.015	.0051	.0021	.0008	.00018	.00005
		500	.071	.035	.016	.0058	.0026	.0011	.00031	.00010
	F	100	.074	.046	.020	.0050	.0017	.0005	.00010	.00003
		200	.075	.048	.021	.0059	.0022	.0008	.00017	.00005
		500	.076	.049	.022	.0066	.0027	.0011	.00031	.00010
10	D	100	.493	.235	.103	.032	.012	.0039	.00077	.00021
		200	.504	.245	.112	.038	.015	.0058	.00133	.00039
		500	.511	.252	.118	.043	.019	.0083	.0023	.00077

the results are deposit densities at least an order of magnitude higher in neutral conditions with strong winds then in typical summer cases with light winds, and a rapid fall-off of deposit with increasing distance.

The estimates are in broad agreement with some drift deposits measured downwind from a 200m long field by Nordby and Skuterud (1975), with a boom height of 0.4m and fan jets operated at 250kPa. At low wind speeds ($1.5ms^{-1}$) the measured deposits at 5 and 25m from the field edge were about 0.03 and $0.01gm^{-2}$, fairly close to Table 8's values for daytime conditions with the same spraying rates. Measured deposits at these distances in winds of $4ms^{-1}$ were 3 to 5 times higher, fairly consistent with Table 8 but showing a somewhat slower fall off with distance than the tabulated estimates. The estimates may also be compared with results of spray experiments carried out by NIAE (NIAE 1969) in winds averaging about $5ms^{-1}$. The experimental data showed considerable scatter, with sometimes the measured deposits at distances of 100m or so exceeding those much closer to the source; on average they gave deposit densities of about $0.3gm^{-2}$ at 7.5m, and $0.02gm^{-2}$ at 100m, in each case downwind of a 400m long sprayed area, and again fairly consistent with the results in the Table.

It appears therefore that the simple physical arguments used in the present report to estimate source strengths (i.e. initial drift) and consequent deposit densities produce realistic values. The estimates may of course be refined to allow for the effects of droplet evaporation on deposit densities, and theoretical treatments of droplet drift could certainly be developed to take evaporation into account. However it is probably more profitable at present to attempt to gain more insight into those processes which control the numbers and spectra of the drops which escape from the spray fan to become drift. Factors which should be considered here (apart from wind speed) are atmospheric stability, spray pressure, boom height and boom bounce; the required information will probably have to come from experimental rather than theoretical studies, with much of the work being carried out in the field and not in wind tunnels.

(c) The hazard from vapour volatolizing from a sprayed surface

Damage to sensitive plants caused by herbicide vapour drifting from areas sprayed by fairly volatile chemicals has occurred apparently on numerous occasions in recent years in Britain. The present report is not concerned with estimating the rate of production of such vapour, but solely with the way in which the vapour is dispersed downwind by atmospheric turbulence. It might be thought appropriate to note that those conditions likely to lead to the highest rates of production of vapour (i.e. high surface temperature) are also those when atmospheric turbulence will be more effective in reducing the concentration of the vapour as it drifts downwind: conversely the night time conditions in which the vapour is diluted much less rapidly as it travels downwind are also those in which the production of vapour will be low because of the lower temperature then. However the daytime conditions in which high temperatures occur are usually those with light and unsteady winds when the direction of drift of vapour volatalised in the next few hours following spraying (or during the following day) is difficult, sometimes impossible to predict; this factor usually overides completely the advantage of a relatively high rate of dilution of the vapour as it drifts away from the sprayed area.

An approximate estimate may be made of the deposit density $\mathbf{D}(x)$ per square metre at different distances downwind from a source consisting of vapour evaporating from a strip 1m wide sprayed on a line at right angles to the wind and emitting a total of 1 unit of vapour per square metre. The estimate follows from a treatment by Pasquill (1961) who showed that

$$D(x) = v_d \sqrt{\frac{2}{\pi}} \cdot \frac{1}{\bar{U}\sigma_z} \qquad (5)$$

where $\bar{U}$ = mean wind speed

σ_z = standard deviation of the vertical distribution of vapour at distance
= 0.47 x height of vapour cloud (Figure 1)

v_d = "deposition velocity" (see below)

This treatment assumes that the distribution of vapour in the vertical is normal (Gaussian), and that the rate of depletion of vapour in the drifting cloud by deposition on the underlying surface is small. Deposition is represented here by the "deposition velocity", which is the equivalent settling velocity of the vapour cloud which would produce the same surface deposit.

The mechanism of deposition will not be discussed here in any great detail, although it is critical to the value of v_d which is used. A study by Fowler and Unsworth (1979) of SO_2 transfer to wheat showed that largest deposition to a dry crop occurred when the leaf stomata were open, with the deposition velocity then around 0.01 ms^{-1}. The values with closed stomata were several times smaller, and there was evidence in these latter (nocturnal) conditions that uptake of the SO_2 was then primarily by the soil rather than the plants. It is not clear what the pathway for the absorption of the spray chemical vapour by the plant will be, but if it is the stomatal one then it is probably appropriate to assume that uptake by plants at night is negligible. The daytime value of v_d will depend on the molecular diffusion coefficient of the vapour in air (which influences the rate at which vapour will diffuse through the stomata): if the vapour has a high molecular weight the deposition velocity will be less than that for SO_2. In the absence of further information the values v_d = 0.01 ms^{-1} by day and v_d = 0 at night will be used to calculate vapour deposition to the plants. The results to be given may be corrected readily if other values for the deposition velocity are found to apply.

Table 9 summarises the results of calculations carried out for field widths and downwind distances similar to those used in § 4(b) for droplet drift. Assumptions include a vapour source of 1 unit m^{-2}, and a wind speed of 2ms^{-1}: vapour deposits for other wind speeds $\bar{U}$ but the same stability category may be obtained by multiplying the results in the Table by $2/\bar{U}$.

Table 9 Vapour deposit densities downwind from fields emitting 1 unit of vapour per square metre (deposition velocity = 0.01 ms^{-1})

Downwind distance from field edge (m)	Deposit densities (units ms^{-2})								
	Field length = 100m			200m			500m		
	A	B	D	A	B	D	A	B	D
5	.091	.141	.226	.113	.180	.307	.145	.234	.407
10	.073	.116	.190	.094	.153	.269	.126	.207	.368
20	.056	.090	.153	.075	.125	.228	.106	.177	.324
50	.035	.058	.105	.052	.089	.162	.081	.137	.260
100	.023	.040	.073	.039	.065	.120	.062	.107	.209
200	.014	.025	.047	.025	.043	.082	.045	.082	.157
500	.007	.012	.024	.012	.023	.045	.025	.047	.096
1000	.004	.007	.014	.007	.013	.027	.015	.029	.063

No results are presented for stable (class E and F) conditions because of the probable low rates of volatolisation and small deposition velocities then. The actual magnitudes of these estimates should be treated cautiously because the deposition velocity for vapour may have been substantially overestimated. If the selected value for v_d is correct, then in those conditions most likely to produce substantial volatolisation (high air temperature, light winds, i.e. Pasquill's class A (very unstable) it is seen that the vapour deposit per unit area just downwind of a field 200m long is around 10% of the vapour released per unit area from the field. For volatile formulations the amount of the original deposit which is subsequently volatolised may be tens of per cent in very warm conditions (e.g. Maybanks et. al. (1978) who found that up to 40% of the initial deposit of a butyl ester of 2, 4-D on soil could evaporate within 2 hours in the Canadian prairie summer). It is possible therefore that vapour deposits up to a few per cent of the original spray deposit may build up near the downwind field edge. More information on v_d will be needed to confirm this estimate. Less speculative is the likely variation of vapour deposit with increasing downwind distance. For the 200m long field, deposits 100m downwind will be 25% or more of those close to (just downwind from) the field edge, and at 1 km will be at least 5%. It is easy to understand therefore the threat which volatile formulations of herbicides pose to sensitive off-target crops!

5. Concluding remarks

The various physical treatments outlined in the previous sections and used to quantify the meteorological factors affecting spray drift and deposit all incorporate major simplifying assumptions. However the estimates they produce for drift deposit densities appear to be in broad agreement with admittedly limited experimental results.

Crucial to our understanding of spray drift is the determination of the number and size spectrum of drops which became truly airborne after emission, and although some ideas on how to estimate these quantities in light and strong winds have been put forward here, it is clearly necessary to develop methods of providing this information under less restrictive conditions. The problem does not appear to be very tractable from a theoretical standpoint: to secure the required information experimentally would require a substantial effort, but the importance of the subject may well justify such work. One is perhaps seeking here spray samples collected by a rig towed a metre or so downwind of a spray jet but not coupled directly to the boom so that the effects of boom bounce may be properly sampled. The aim would be first to quantify (within a factor of better than 2?) the numbers (and size spectrum) of drift drops occurring for any realistic combination of meteorological conditions, hydraulic pressures, boom height and boom bounce, and second to give the effective height (or height range) of emission of drops of different sizes.

The approximate treatment which has been used in § 4(b) to estimate drop deposit densities downwind of the source area does not lend itself to the incorporation of what may be significant effects due to drop evaporation. A "random - walk" turbulence model similar to that described by Hall (1975) is likely to be more suitable although it is much less efficient computationally, involving the calculation of individual trajection of thousands of evaporating and sedimenting individual drops. Again a selection of experiments would be needed to verify the theoretical treatment before it could be applied widely with confidence.

The calculations in § 4(c) of vapour deposit densities on crop-covered surfaces downwind of inadvertently volatolised spray deposits are fairly straightforward. The results however must be viewed cautiously until more information becomes available on likely rates of volatolisation under various meteorological conditions, and also on the magnitude of the "deposition velocity" of this vapour onto the

sensitive crop which lies downwind. These pieces of information, used in conjunction with the results presented here, should allow a ready quantification of this unwanted side effect of crop spraying.

Any comments or suggestions on this paper should be referred to the author.

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